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ADVANCED AEROPROPULSION CONTROLS TECHNOLOGY

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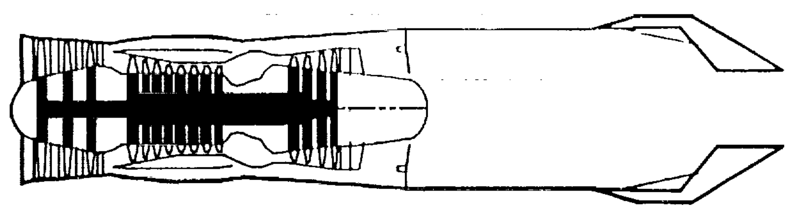
This paper discusses NASA Lewis' research activities in the area of propulsion control as driven by the trends and needs of advanced aircraft. Special emphasis is placed on research to develop design methodologies for integrated flight and propulsion control. The paper also covers research thrusts in hypersonic propulsion control and dynamics in support of the National Aerospace Plane, and a new concept for system critical component life-extending control is discussed.

Thrusts in Aeropropulsion Control

- Achieve the highest possible performance from the propulsion and aircraft systems
- Manage the dynamic coupling now being designed into advanced aircraft
- Minimize damage accumulation in system components
- Increase the availability of hardware through advanced control intelligence



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The fundamental goals in aeropropulsion are toward lower weight, higher reliability, and higher performance systems. Improved performance takes the form of exotic special-purpose aircraft (such as supersonic short-takeoff, vertical-landing (STOVL) aircraft, the National Aerospace Plane (NASP), and X-Wing Convertible-Engine Rotorcraft). The challenge of advanced controls is to provide the intelligence and coordination so that the system components can realize the performance gains strived for at the component technology level and to maximize the reliability and utility of the new vehicles with their increased dynamic coupling between the vehicle and propulsion systems.

Project Focus Areas of Lewis Aeropropulsion Controls Program

- National Aerospace Plane—Propulsion system dynamic modeling and control
- Supersonic STOVL propulsion—flight control integration
- Life-Extending Control

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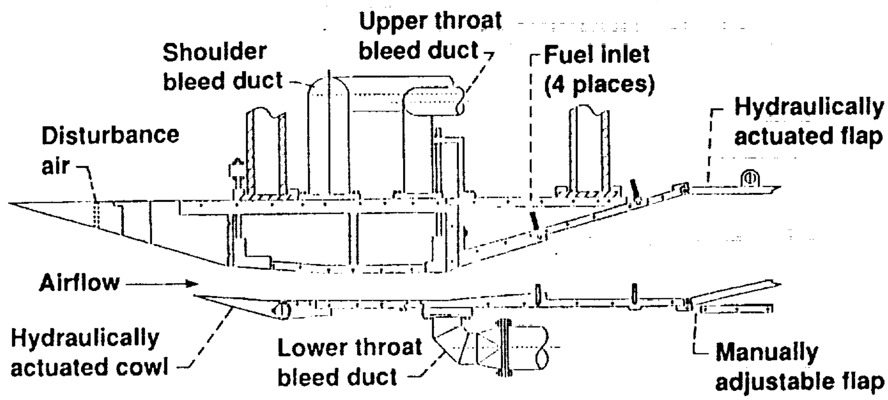
The Lewis Aeropropulsion Controls Program addresses the basic thrusts through focused studies of advanced aerospace vehicles and propulsion systems of broad interest.

NASP Propulsion System Dynamic Modeling

Objectives:

- Formulate dynamic models of NASP propulsion systems for control design and operability assurance
- Validate model through dynamic testing at selected operating conditions
- Determine transient and frequency responses, inlet unstart characteristics, and engine-to-engine interactions



Modified Government Baseline Engine

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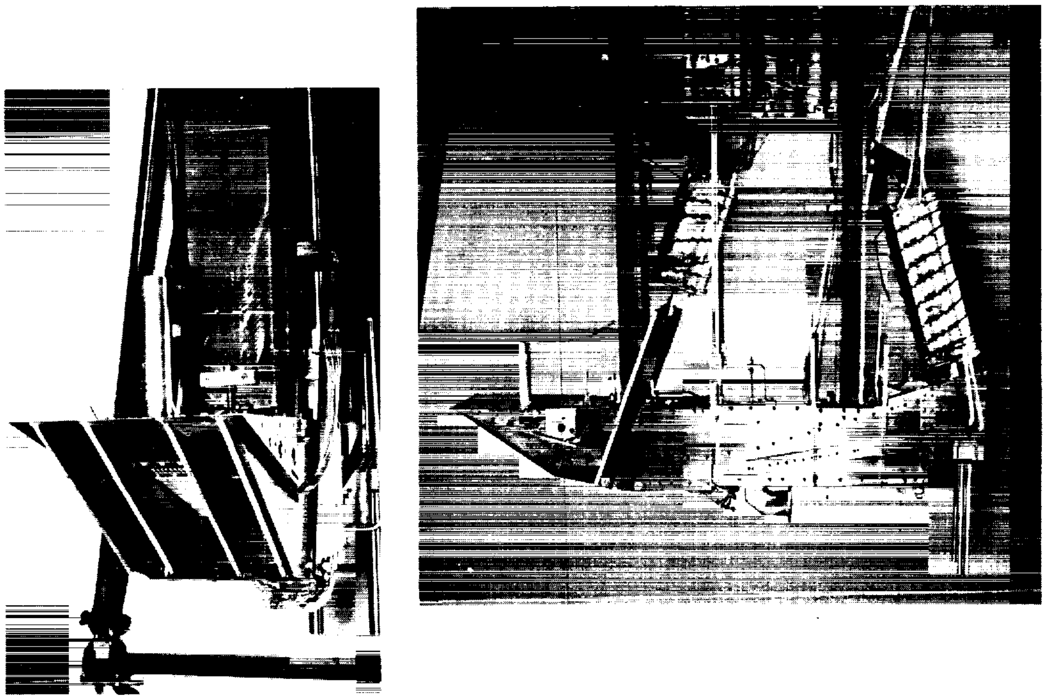
The NASP Propulsion System Dynamic Modeling Program seeks to create transient models of representative hypersonic propulsion systems. The intended uses of these models are to expose any broad operability problems and contribute to their resolution and to serve as a basis for hypersonic engine controller design.

The models that have been created are nonlinear, one-dimensional, transient codes that describe the overall behavior, including variable-geometry effects and combustion. These models are relatively simple to allow near-real-time operation for controls design but have sufficient fidelity to allow study of such problems as inlet unstart.

The Modified Government Baseline Engine (MGBE) is the focus of current modeling efforts.

Modified Government Baseline Engine



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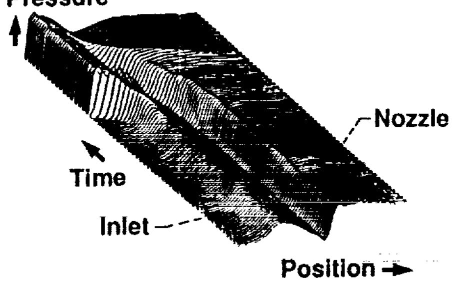
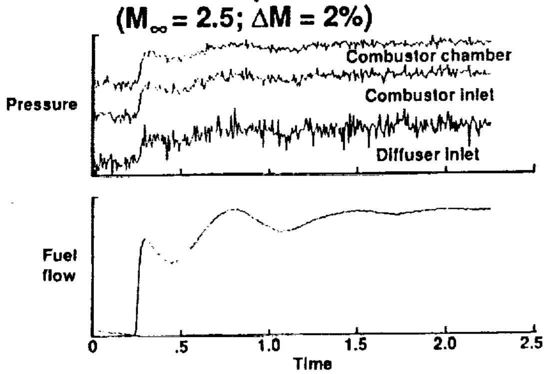
The Modified Government Baseline Engine (MGBE), shown here, is being used to validate the dynamic model as well as the propulsion control design. The center duct is the active engine, and the two side ducts simulate adjacent engines. Their purpose is to allow engine-to-engine interaction to be studied.

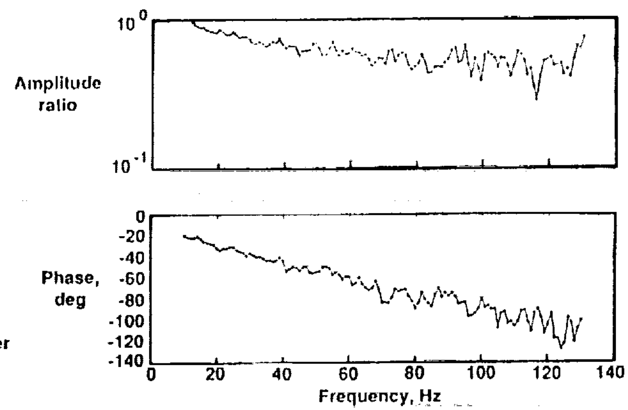
Hypersonic Propulsion System Dynamic Modeling and Test Results



Simulated engine unstart due to inlet Mach number perturbation ($M_\infty = 2.5$; $\Delta M = 2\%$)



Response of engine pressures to step in fuel flow



Combustor-pressure-to-fuel-flow transfer function

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The figure shows a simulated engine unstart due to an inlet Mach number perturbation. At some time $t_0 + \Delta t$, a Mach number perturbation is introduced into the inlet of the one-dimensional simulation. The Mach wave reflects off the nozzle and travels back upstream, unstarting the engine.

The response of MGBE pressures (actual data) to a step in combustor fuel flow (calculated from manifold pressures) is also shown. At about 0.25 sec the fuel flow is stepped up. Shortly thereafter the engine pressures follow. Close inspection shows that the combustor inlet pressure rises first, followed by combustor chamber pressure and diffuser inlet pressure, respectively. The large low-frequency perturbation is the fuel system dynamics settling out after the request for increased flow.

A typical transfer function for engine combustor pressure to fuel flow is shown. A frequency sweep test signal was applied to the main fuel valve. The resulting transfer function shows that over the frequency range the engine exhibited a dead time of about 4 msec.

Hypersonic Propulsion System Control

Objectives:

- Determine practical methods of control for hypersonic propulsion systems
- Evolve control design and design method for Modified Government Baseline Engine
- Validate through testing
- Demonstrate
  - Shock position management
  - Thrust control
  - Mode transition control (start/unstart/restart)

Inlet view of Modified Government Baseline Engine

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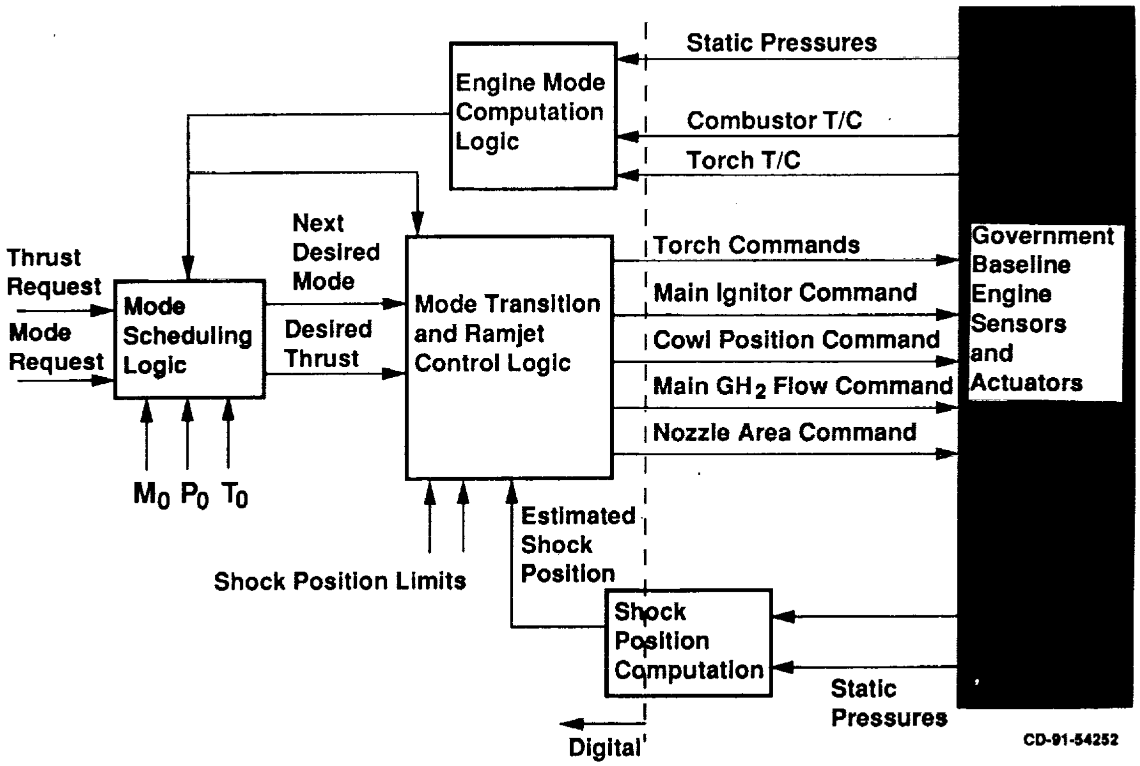
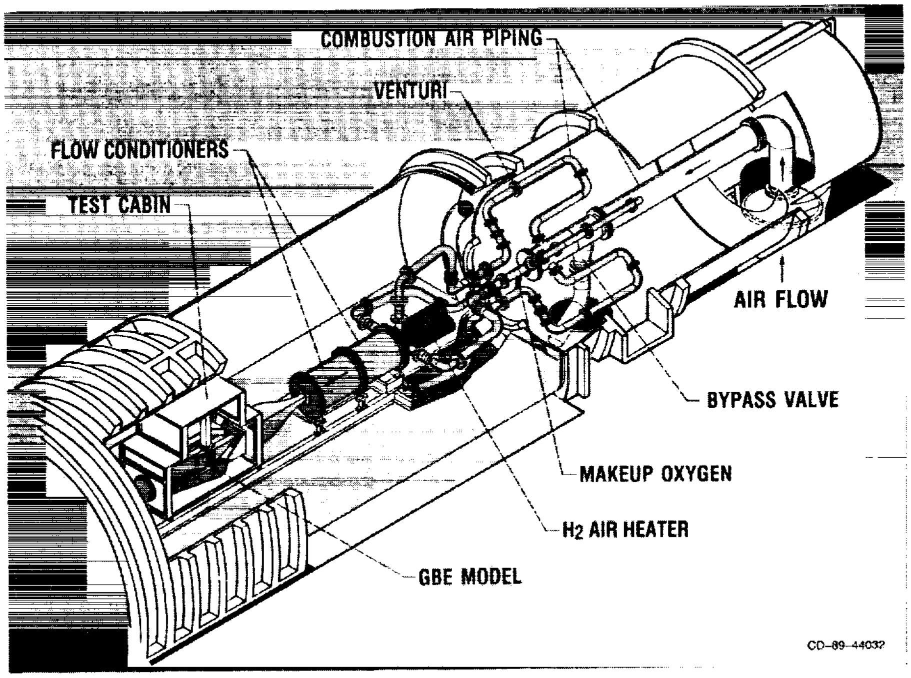
The thrust of this activity is to establish reasonable and practical control design approaches for hypersonic propulsion systems. The management of these complex multimode machines presents challenges in shock position management, thrust control, and mode transition control. Of particular importance is the issue of inlet unstart/restart management through coordinated control of engine fuel flow and variable geometry.

Modified Government Baseline Engine Control Logic Diagram



This figure is a block diagram of the engine control logic to be tested in the Lewis Propulsion System Laboratory (PSL-4). The logic performs four basic functions: (1) it computes the next desired engine mode and thrust level given a thrust and mode request; (2) it determines the present engine mode from sensor data; (3) it computes the location of the engine's internal shock train; and (4) it produces commands to the engine's valves and variable-geometry actuators. The control logic runs on microprocessor-based, special-purpose control computers. A series of PSL tests will be run to demonstrate the control's ability to rapidly modulate engine thrust and also to hold thrust constant in the face of externally imposed disturbances.

MGBE PSL–4 Installation



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The MGBE engine control will be validated by tests in the modified Propulsion System Laboratory facility shown here. The facility enables continuous free-jet testing of engines in this size class. A hydrogen-fueled preheater provides flow at appropriate temperature to a Mach 3.5 nozzle with makeup oxygen to allow proper engine combustion. Run time is limited by the thermal capacity of the engine model.

Flight and Propulsion Control Integration

Objectives:

- Enhance, create, apply, and validate methodologies for designing and implementing integrated flight and propulsion control systems

Goals:

- Expand DMICS methodology beyond conventional-takeoff-and-landing (CTOL) aircraft
- Create advanced integrated control methodologies
- Apply methodologies to STOVL aircraft configurations over the complete flight regime
- Evaluate integrated control in a simulated flight environment
- Address control hardware technology requirements such as architecture, processors, and control components

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New and advanced aircraft concepts such as Supersonic STOVL, X-Wing rotorcraft, and hypersonic vehicles derive significant performance gains by allowing high levels of dynamic coupling not normally associated with conventional aircraft. The cost of this dynamic coupling is either increased pilot workload or a requirement for the control system to unify the behavior of the flight control and propulsion control systems. The goal of this effort is to create an integrated control design methodology that yields globally optimal performance with reasonable pilot workload.

Supersonic STOVL Flight and Propulsion Control Integration Program Elements

E7D/F110 STOVL integrated flight and propulsion control study:

- **Apply DMICS methodology to STOVL aircraft**
  - Ejector-augmented STOVL configuration (E7D/F110)
- **Evaluate control concept with real engine and simulated aircraft in ground-based test**
- **Evaluate control concept and handling qualities on Ames VMS**

Integrated Methodology for Propulsion and Airframe Controls (IMPAC):

- **Establish advanced integrated control methodologies for Supersonic STOVL aircraft**
- **Design candidate control concept and evaluate and validate system in piloted simulation and in ground-based experimental program**

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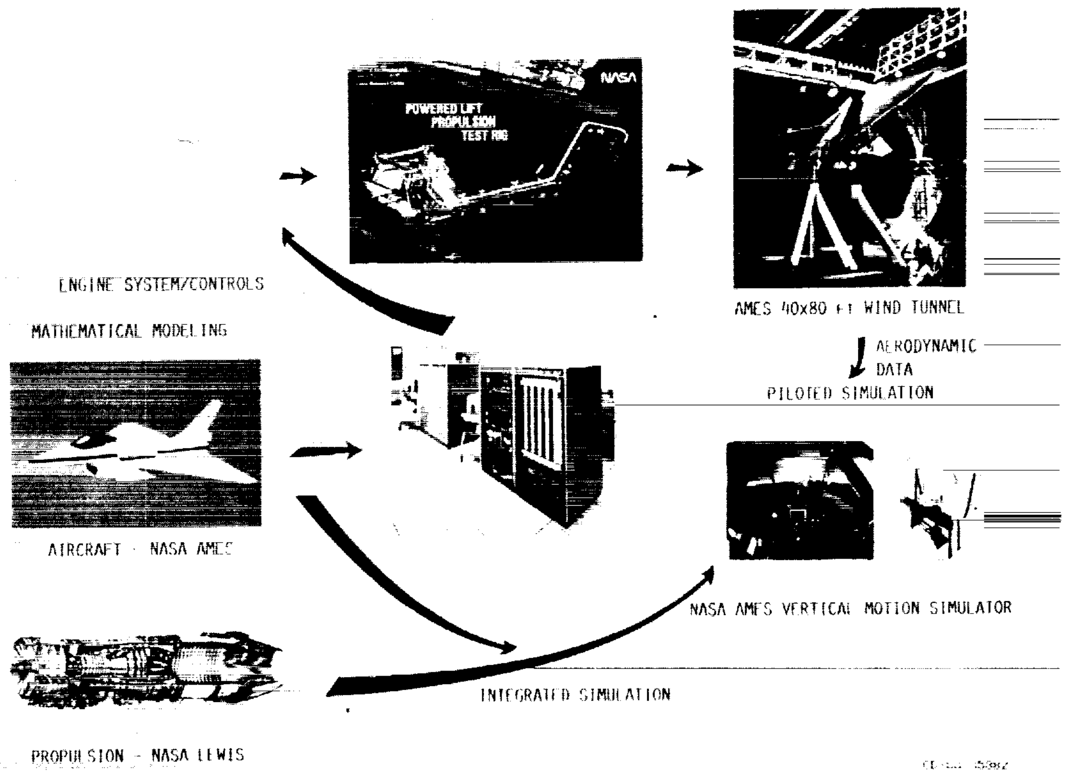
The Lewis Integrated Flight and Propulsion Control Program has two major components: (1) the E7D/F110 STOVL program, which is a contract effort with General Electric and General Dynamics and applies the Air Force-developed Design Methodology for Integrated Control (DMICS) and (2) an in-house effort called Integrated Methodology for Propulsion and Airframe Controls (IMPAC). Both efforts are coordinated with NASA Ames and plan validation tests on the Ames Vertical Motion Simulator.

INTEGRATED CONTROLS RESEARCH DEMONSTRATOR PROGRAM



The NASA Lewis integrated controls research demonstrator program consists of two major paths for validating and demonstrating Integrated Flight Propulsion Control (IFPC) design methodologies for STOVL aircraft. One research path culminates in a piloted simulation of the target STOVL aircraft at the NASA Ames Vertical Motion Simulator. Piloted simulation will establish the handling qualities of a STOVL aircraft with a candidate IFPC concept. This work entails developing mathematical models for both the airframe and the propulsion system. The airframe model is formulated from aerodynamic data obtained from wind tunnel tests of the target airframe conducted by NASA Ames. The propulsion system model is based on existing gas generator systems augmented with STOVL-specific component data obtained by experimental testing conducted at NASA Lewis. The IFPC system was designed with control design methodologies developed both in-house at NASA Lewis and by industry.

The second research path involves propulsion system testing at NASA Lewis. This test involves actual propulsion system hardware, consisting of a current-technology gas generator and STOVL-specific, thrust-producing components (e.g., ventral nozzles and ejector nozzles). Computer-based, real-time models of the airframe and IFPC logic complete the overall test system. These tests will investigate the performance of a STOVL propulsion system with an IFPC. Propulsion system data obtained from this testing will be used to enhance the propulsion system models for the piloted simulation work. Together both the piloted simulation and the propulsion system testing will establish the validity of integrated control concepts for use in STOVL aircraft. (Funding for testing in the second research path has not yet been established.)

IMPAC—Integrated Methodology for Propulsion and Airframe Controls

Objective:

- Develop and demonstrate through the in-house Lewis program a centralized IFPC design methodology

Method:

- Demonstrate IMPAC design methodology for E7D SSTOVL aircraft through Lewis and Ames piloted simulation

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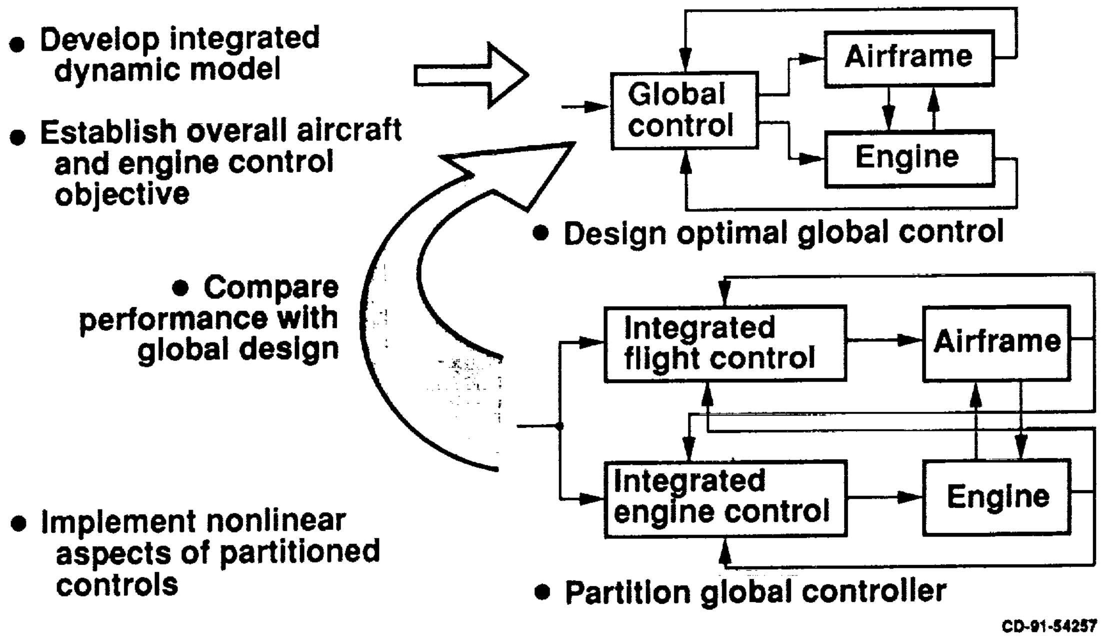
The objective of the IMPAC program is to develop and demonstrate a methodology for Integrated Flight and Propulsion Control (IFPC) design for future aerospace vehicles with a high degree of coupling between airframe and propulsion systems. The methodology to be developed will provide a viable alternative to the methodologies developed under the Air Force DMICS program while allowing for improved system performance and greater simplicity of control law synthesis and implementation. The three main phases of IMPAC are (1) methodology development, (2) IFPC design for the E7D SSTOVL aircraft, (3) methodology demonstration through piloted-simulation evaluation of the E7D aircraft on the Lewis and Ames simulators. Since both IMPAC and the Lewis-managed STOVL controls program are using the E7D test bed, the strengths and weaknesses of the IMPAC global and DMICS partitioned methodologies can be directly compared.

Integrated Methodology for Propulsion and Airframe Controls

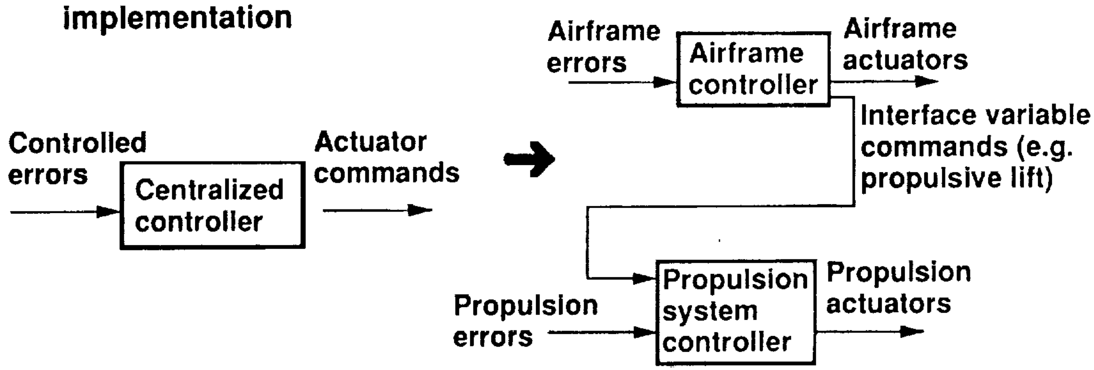


The IMPAC methodology consists of the following steps:

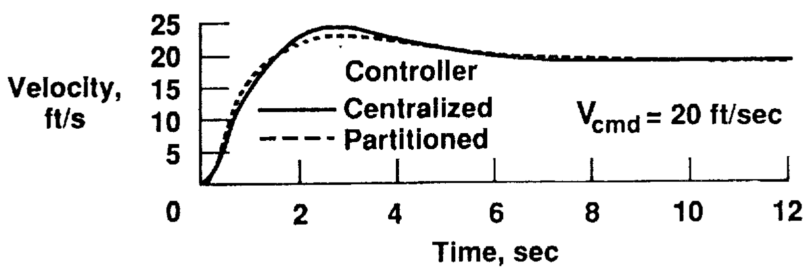
(1) Developing fully integrated dynamic airframe and propulsion system simulations, and generating linear models for control design
(2) Establishing the airframe and engine control objectives
(3) Performing the global control design to meet the control objectives
(4) Partitioning the centralized controller into separate airframe and propulsion system controllers for simplicity of implementation and independent subsystem checkout and performance accountability. This partitioning is to be done such that the integrated system performance with the partitioned controllers is close to the "optimal" performance with the centralized controller.
(5) Implementing the nonlinear aspects of the partitioned subcontrollers for operations over a wide range of flight conditions; incorporating safety limits and limit switching logic; etc.
(6) Evaluating the control design through closed-loop integrated nonlinear simulations and piloted simulations on fixed-base and motion simulators

Controller Partitioning

- **Decentralized hierarchical partitioning for state-of-the-art IFPC implementation**



- **Partitioning theory developed; computer algorithms under development**
- **Initial results encouraging; feasibility demonstrated**



Velocity response for STOL aircraft

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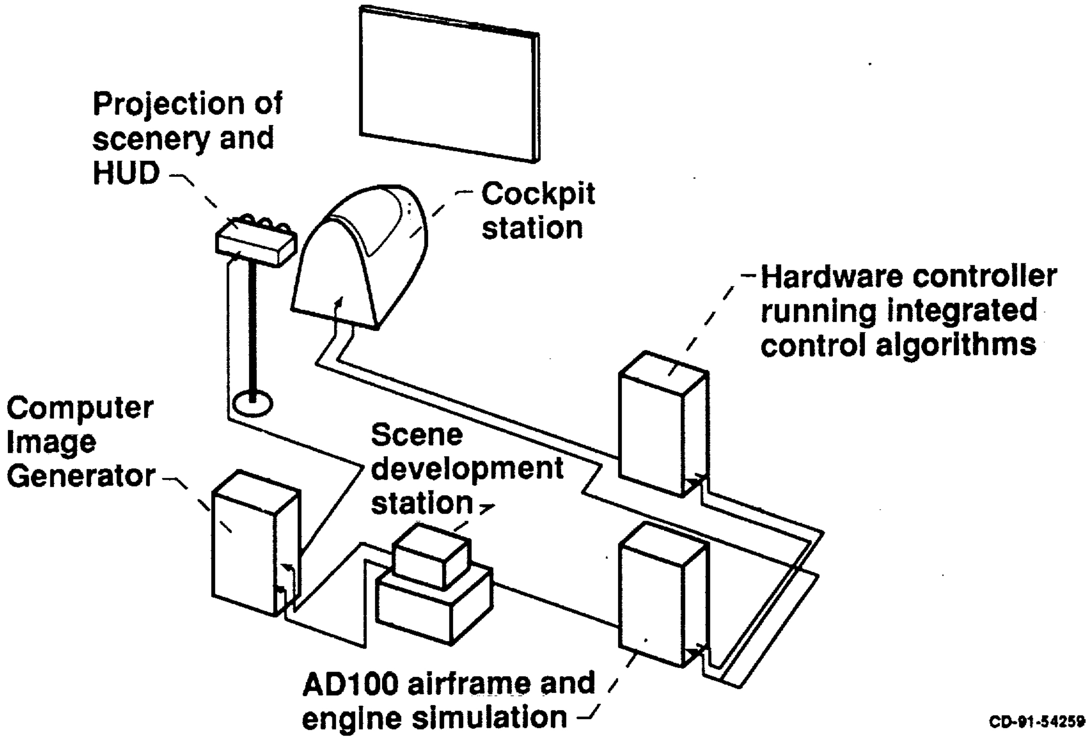
Although the centralized controller designed under IMPAC will be "optimal," it results in one high-order controller that is difficult to implement and crosses lines of corporate responsibility and expertise. Also the propulsion system manufacturer performs extensive tests with an independent subcontroller to ensure an adequate design. To address these difficulties, the idea of partitioning the centralized controller into separate airframe and propulsion subcontrollers has been introduced through the Lewis program. The partitioning "best" suited to IFPC implementation is one that results in a hierarchical structure for the propulsion subcontroller.

The theoretical solution of the decentralized, hierarchical controller partitioning problem for IMPAC is essentially complete. Numerical algorithms to implement the partitioning solution are currently being developed. Shown in the accompanying figure are responses of the IFPC system for a STOL aircraft to a step velocity command with a centralized controller and with an initial decentralized hierarchical controller obtained by partitioning. These initial results are quite encouraging and demonstrate the feasibility of the controller partitioning concept.

NASA Lewis Integrated Propulsion and Flight Control Simulator



The integrated propulsion and flight control simulator at NASA Lewis is a low-cost, real-time, fixed-base simulator used for integrated propulsion and flight control algorithm development, analysis, and evaluation. This simulator is used to evaluate both engine and airframe control performance in real time. With this evaluation capability the NASA Lewis flight simulation facility allows for rapid prototyping of integrated flight and propulsion control algorithms. Additionally, this simulator facility configuration provides easy, immediate access to engine and airframe data, interface variables, and control variables. Through the use of this flight simulator, integrated control algorithms are more readily tested, evaluated, and debugged prior to their evaluation on larger, motion-based flight simulation facilities.

The facility consists of a Computer-Generated Imagery (CGI) system; a single-channel projection system; a mockup fighter cockpit with sidestick controller, throttle, and rudder pedals; and a color touch screen monitor to emulate heads-down instrumentation in the cockpit. The AD100 simulation computer is used to drive the host engine and airframe simulations. The Control Interface Monitoring (CIM) unit executes the integrated control algorithms. The CIM unit is microprocessor based and fabricated in-house for the purpose of implementing and evaluating advanced digital control algorithms.

Status of Integrated Methodology for Propulsion and Airframe Controls

- Centralized design approach selected as primary thrust
- IMPAC methodology framework formulated
- Global controller partitioning theory and programs in development
- Effort to address nonlinear effects started
- Initial IFPC design for transition flight condition completed and published
- IMPAC methodology to be demonstrated in FY '91 in Lewis flight evaluation station

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The IMPAC program has established the framework of a global integrated control design methodology. Partitioning methods have been established and computer programs are now being implemented to perform the required calculations. The goal now is to complete a control design including nonlinear effects for the E7D/F110 supersonic STOVL aircraft and to evaluate the design through real-time, pilot-in-the-loop simulation.

Life-Extending Control Concept

Control rates of change and levels of some performance variables to minimize damage of critical components while simultaneously maximizing dynamic performance

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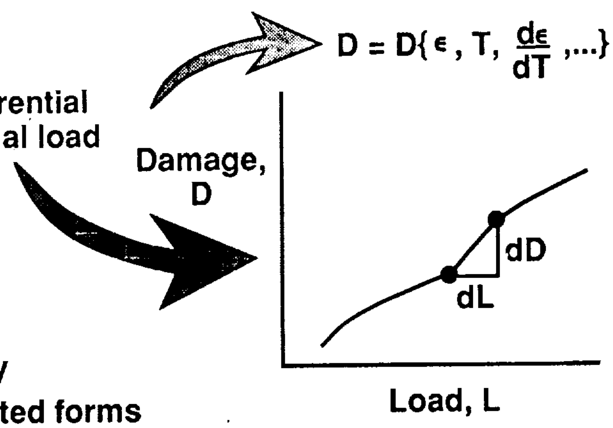
Systems with high performance requirements often have a small number of components that operate close to mechanical design margins. These critical components usually define the effective lifetime of the system and/or the mean time between maintenance actions. An active approach to managing the lifetime of these critical components can extend the time between maintenance actions or increase the total mission effectiveness of the system. This may be particularly true of systems that have long expected lifetimes, multiple mission objectives, and limited access to regular maintenance.

The concept of Life-Extending Control (LEC) means the management of the resource of component lifetime and the achievement of a desired objective. The desired objective is usually defined in terms of system performance. The concept depends on a prediction of the fatigue life of the particular component (or components) in the system. The component is assumed to be the life-limiting element or the most likely candidate for mechanical failure within the system. Currently, the fatigue life prediction of this component is based on a local, cyclic strain approach. The prediction of the remaining life of the component as well as an understanding of the effects of cyclic loading, stress, and strain on remaining life enable a quantification of the tradeoff between system performance and life to be established for a dynamic system. Once this tradeoff is defined, a control that maximizes system performance for a given lifetime of the component (or conversely, that minimizes damage for a given system performance) can be designed.

Continuous Life Prediction Approach
(Proposed)

Objective:

- Functionally relate differential damage with differential load (through local strain, stress, etc.)



Approaches:

- Derive from basic theory
- Empirically select expected forms and use optimization to best fit parameters

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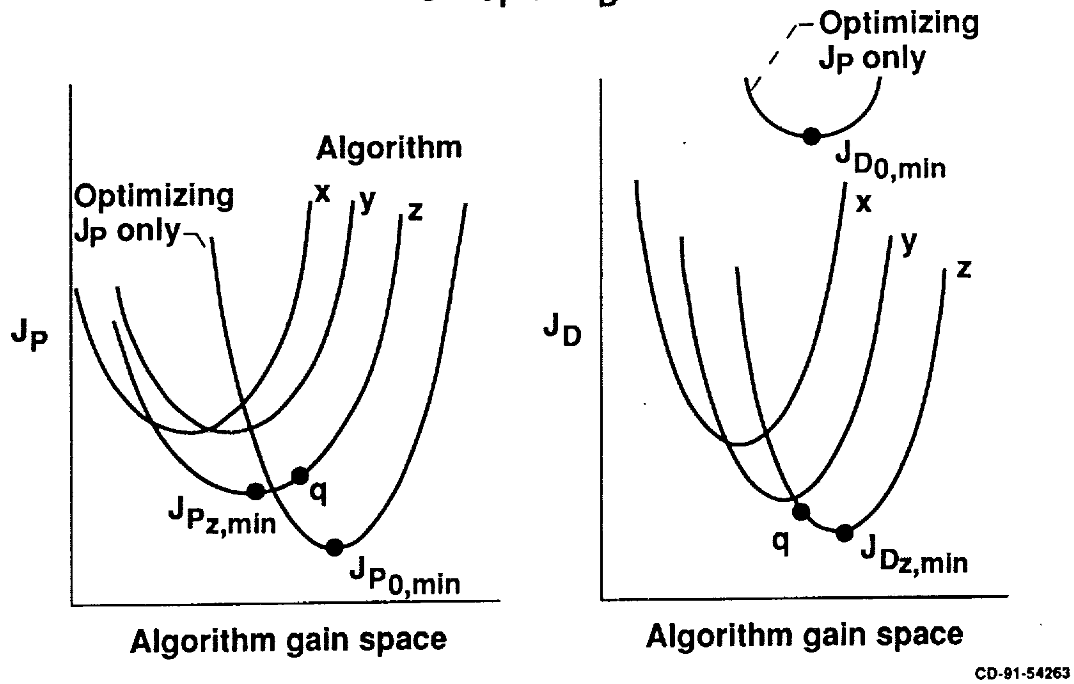
Current life prediction methods are cycle based. The cyclic life prediction process is highly nonlinear and comes from the study of metal fatigue due to cyclic loading. Usually the life estimates that result are used to forecast service life for a particular component design. The cyclic damage approach predicts damage over a stress-strain cycle based on material constants, average tensile stress, and cycle stress-strain amplitude. Total damage is then estimated by summing the cycle-by-cycle damage. Indirect life-extending control methods based on this type of damage model are now being studied.

However, the direct application of a life estimation procedure to control would be more beneficial and is therefore the ultimate goal of life-extending control. To accomplish this goal, a new formulation of the life estimation procedure is required. This new formulation will consist of a continuous form of the damage laws instead of the current forms, which require bookkeeping the number of cycles, their respective amplitudes, and their order of occurrence.

To achieve a continuous formulation of the life prediction process, an interdisciplinary approach is being used. Here the knowledge of material properties and life prediction of fracture and fatigue scientists must be combined with the control engineer's knowledge of dynamics and modeling to develop these continuous forms. The objective is to functionally relate measurable performance information with a differential form of the damage laws. This will allow the direct use of the differential estimate of damage in the life-extending control law and when integrated over complete cycles will give damage predictions that are equivalent (or perhaps superior) to those associated with the cyclic theory.

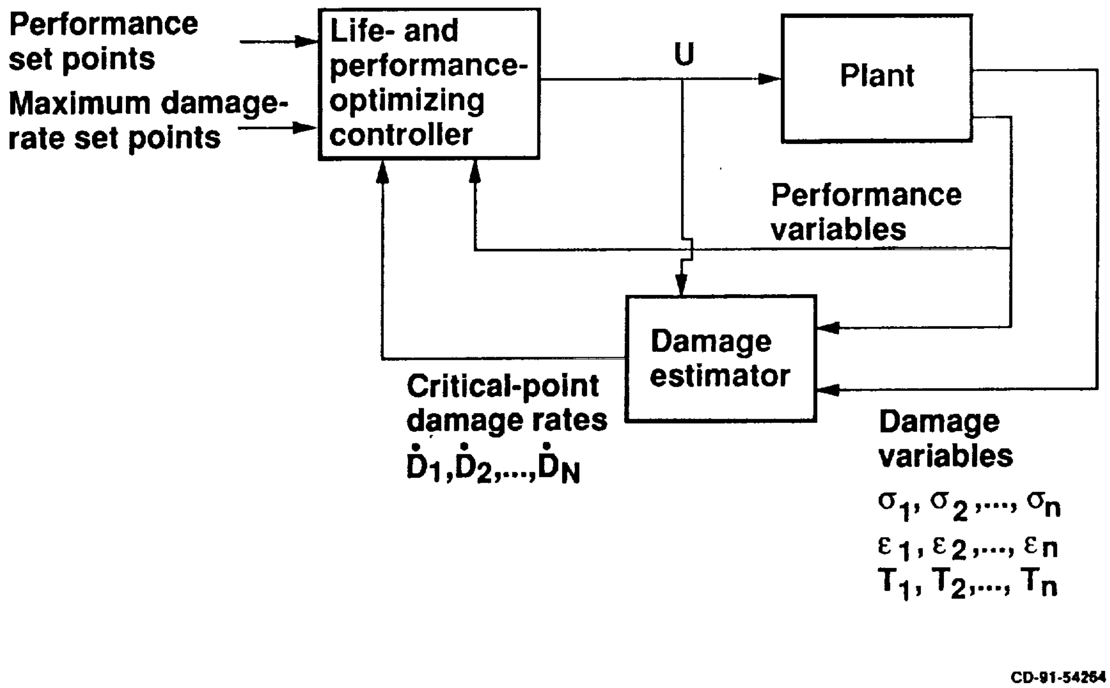
Effect of Various Life-Extending Control Algorithms on Performance J_P and Damage J_D

$J = J_P + aJ_D$



Two performance measures are considered: J_P, an objective function that maximizes dynamic performance, and J_D, a damage measure that uses the best (current) fatigue/fracture theory available to calculate the damage accumulated over the sequence of command transients. An overall performance measure can also be defined as $J = J_P + aJ_D$, where a represents the relative importance between performance and life extension. The basic concept is that designing a control for performance only would allow $J_{P_{0,min}}$ to be achieved. By introducing a good life-extending control algorithm, satisfactory dynamic performance $J_{P_{z,min}}$ (or q) can be achieved while significantly reducing damage from $J_{D_{0,min}}$ to $J_{D_{z,min}}$ (or q). Here, the point q is a compromise gain that allows good dynamic performance and damage reduction.

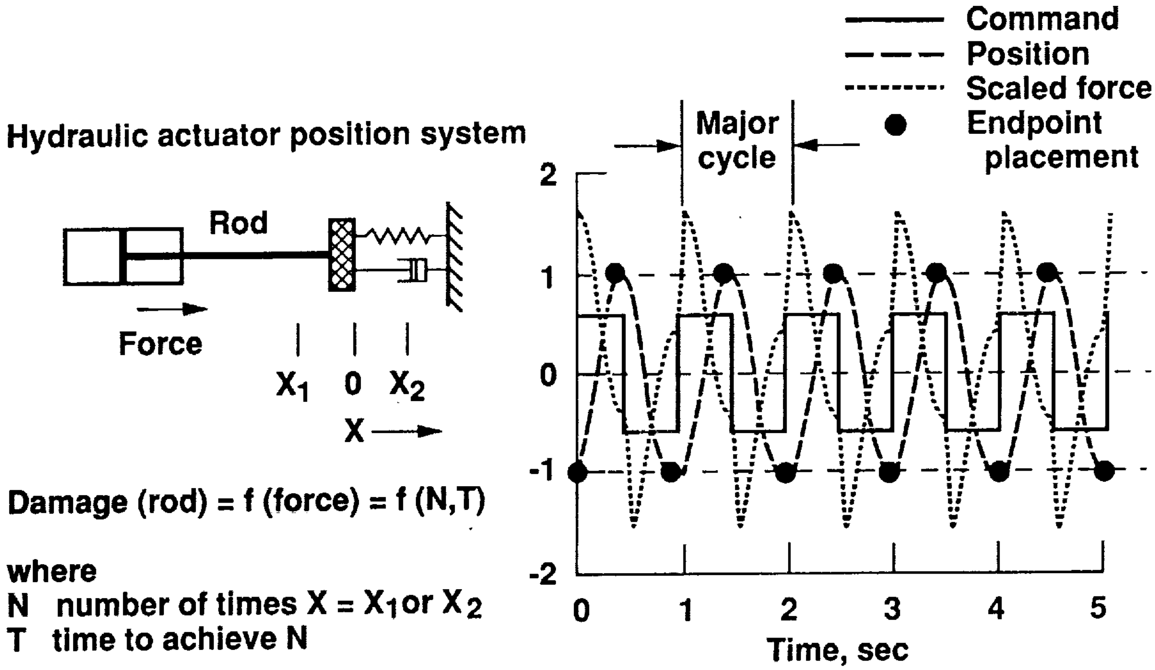
Life-Extending Control



One of several Life-Extending Control (LEC) concepts that is currently being studied is shown in the figure. This concept assumes the availability of a continuous-damage model. Damage variables (stresses, strains, and temperature) are used to estimate the instantaneous rate of damage accumulation at selected critical points of the structure being controlled. The damage rates are then used by the control to optimize dynamic performance while minimizing damage rate.

Life-Extending Control

An Actuator Example



Example results for case 1 trajectory command

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A simple hydraulic actuator example for the positioning of a control surface is used to illustrate Life-Extending Control. The assumptions are that the actuator rod is the life-critical element and that its life is the resource to be managed while obtaining system performance. System performance is defined in terms of a positioning task. The mass at the end of the rod has to be placed, alternately, at positions X_1 and X_2. The number of placements (i.e., the number of times X equals X_1 or X_2) is N. Also, the time to achieve N is T. The performance is then defined to be

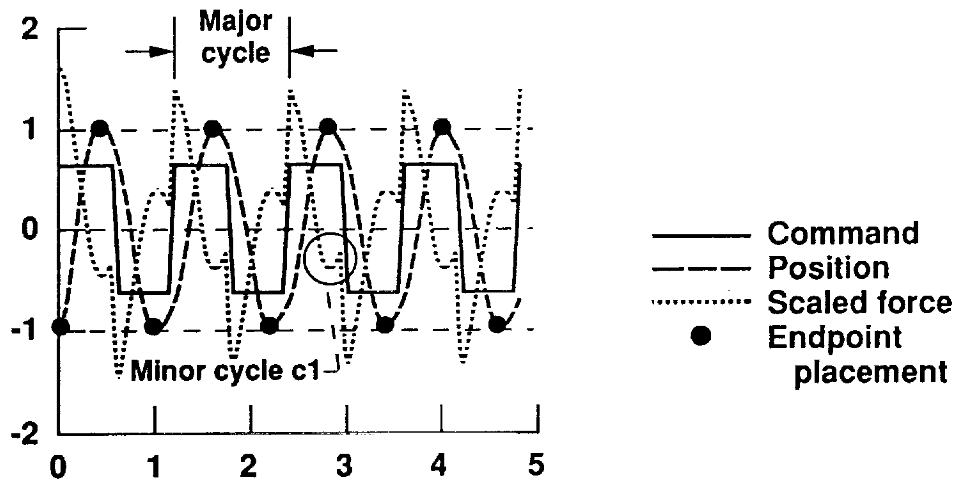
$$P = C_N N - C_T T$$

The first term in the equation is related to dynamic system performance, and the second term is related to accumulated damage. Here N is the number of times a command is given to move the control surface, T is the time required to achieve the desired commanded position, and the constants C_N and C_T represent the tradeoff between positioning accuracy and time to achieve the position. The life of the rod is a function of the compressive and tensile forces F applied to the rod.

Pulse sequence trajectory 1 was applied to the system. Also shown in the figure are the system position and scaled force trajectory resulting from pulse trajectory 1. The performance endpoints were selected as $X_1 = -X_2 = 1$. In this case $N = 11$ and $T = 4.9$ sec. A damage analysis was done on the simulated force trajectory. Here five major stress-strain cycles were observed and used to calculate damage. In this case $D = 0.0213$ units of damage, based on a total component life of 1 unit, was predicted.

Life-Extending Control

Example Concluded



Example results for case 2 trajectory command

Case	N	T, sec	N/T	F_{max}	Cycles	D	T_f	N_{total}	Performance
1	11	4.9	2.2448	1.6	5 Major	0.0213	230	516	802
2	9	4.6	1.9565	1.4	4 Major, 8 Minor	.0121	380	743	1106

Life-extending-control example results

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A modified commanded pulse sequence trajectory, called trajectory 2, was applied to the same system. The commanded trajectory, the system position, and the scaled force for case 2 is shown in the figure. In case 2, N = 9 and T = 4.6 sec. The damage analysis in this case was based upon an observed count of four major stress-strain cycles and eight minor cycles. In case 2, D = 0.0121. Because the commanded pulse trajectory has been slowed slightly, the resultant force trajectory has smaller peak magnitudes. Consequently, the stress-strain cycles have smaller magnitudes and the damage is less.

Results obtained by assuming that the system will be operated to failure with the two pulse sequences selected are summarized in the table. The time to failure will be T_f = 230 sec for case 1 and T_f = 380 sec for case 2. The number of endpoint placements at T_f is N_{total} = 516 for case 1 and N_{total} = 743 for case 2. Given that the constants of performance are C_N = 2 and C_T = 1, the resultant performance is 802 for case 1 and 1106 for case 2. These performance constants can be interpreted as described above. Case 2 offers better total system performance by adopting a strategy that obtains endpoint placements at a slightly longer time, and results in a much more effective use of the lifetime of the critical component.

Additional Advanced Controls and Dynamics Activities

- Intelligent control of reusable rocket engines (neural-network-based control)
- Wave rotor dynamic modeling
- Reconfigurable control

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Other activities are also being carried forward by the Advanced Controls Technology Branch. These are summarized here and include a very significant effort in Intelligent Controls for Reusable Rocket Engines. This effort is focused on the space shuttle main engine as a generic example.

Summary

Advanced aerospace controls have the potential to

- **Optimize complex system performance**
- **Manage intersystem dynamic coupling to reduce pilot workload**
- **Simultaneously minimize damage to hardware and increase availability of hardware when damage does occur**

The NASA Lewis Advanced Aeropropulsion Controls Program is structured to realize this potential.

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The NASA Lewis Advanced Controls Program is focused primarily on propulsion system dynamics and controls. In a broad sense, this includes flight/propulsion control integration. Its objective is to bring advanced intelligence to complex aerospace systems, thereby achieving maximum steady and dynamic performance while improving system reliability and durability.